A Recurrent Neural Network that Produces EMG from Rhythmic Dynamics
- David Sussillo*, Mark Churchland**, Matt Kaufman*** & Krishna Shenoy*
  **- Stanford University, **- Columbia University, ***- Cold Spring Harbor

It remains an open question how the firing rates of neurons in motor cortex (M1) lead to the EMG activity that ultimately drives movement. Recently, Churchland et al. \(^1\) reported that neural responses in monkey M1 exhibit a prominent quasi-rhythmic pattern during reaching, even though the reaches themselves are not rhythmic. They argued that M1 could be understood as “an engine of movement that uses lawful dynamics”, i.e., that M1 could be viewed as a dynamical system. A major question posed by their work is finding a concise set of equations for a dynamical system that uses rhythmic patterns to drive EMG.

We approached this problem by training a nonlinear recurrent neural network (RNN)\(^2\) to generate the recorded EMG during the same reach tasks used in \(^1\). Because feedback connections endow the system with the ability to change dynamically in time, RNNs are a natural class of models to use when studying cortical circuits.

We trained the RNN to simultaneously generate the EMG activity recorded from three muscles (deltoid, pectoral, and biceps) for 27 ‘conditions’ (reach types). The network was provided with condition-specific static inputs as an initial condition, derived from the actual preparatory activity of recorded neurons (panel A and B). The RNN architecture consisted of a simulated M1 circuit (sM1, 150 neurons), which provided input to three separate spinal cord circuits (sSC1-3, 25 neurons each performing nonlinear filtering of sM1 drive input). **There were only two constraints on the system during optimization: 1) successfully generate the EMG and 2) using regularization techniques, do so as simply as possible.**

After training the RNN, it generated EMG with normalized RMS of 0.04 (panel B).

We examined the network dynamics and uncovered a remarkably simple system that showed similarities to M1 on the individual neuron level (panels C and D). Further, the sM1 circuit exhibited oscillatory dynamics as a major component of the network activity. These dynamics, in turn, drove the spinal circuits to generate the EMG. The dimensionality of sM1 activity during simulation of the plan and movement required 15 principal components (PCs) to capture 99% of the variance, in reasonable agreement with M1 data. The spinal cord circuits required 3-5 PC dimensions.

We investigated the nature of the sM1 population dynamics by applying a recently-developed technique for identifying dimensions containing dynamical structure, jPCA\(^1\). The dynamics in the 1st jPC plane were strongly oscillatory and explained 23% of the variance of the network activity (panels E for monkey J, panel F for the RNN that generated EMG of monkey J). These rotations were produced by dynamics in the RNN whose linear approximation – around a local fixed point – contained strongly oscillatory structure reflected by eigenvalues with a large imaginary component. In addition to the rotational dynamics, we found a strong component of the neural trajectory, roughly orthogonal to the jPC plane (80 degrees), which carried the trajectories into the rotation. This component was similar across all conditions, and is thus captured by the ‘cross-condition mean’. Panel G shows a cartoon from \(^1\), illustrating the idea, while panel H shows data from the sM1 circuit visualized in the space spanned by the jPC plane and the cross-condition mean.

In summary, these simulations provide an existence proof that a dynamical system, when appropriately seeded, can generate the EMG of multiple muscles. Crucially, the dynamics are simple and consist primarily of (1) rotational dynamics and (2) a cross-condition mean that brings the trajectories near the region in phase space where the rotations occur. We emphasize that neither the similarities of the RNN units to M1 neurons, nor the oscillatory patterns were built into the system.

A - Network architecture. Condition-dependent preparatory activity provides the initial conditions (ICs) for the RNN to dynamically generate the EMG output. The RNN has four parts, a simulated M1 and 3 simulated spinal cord circuits, one for each muscle. B - 4 out of the 27 example triplets: input (black), RNN output (blue), and target EMG (orange). C - 4 example PSTHs from M1 from monkeys performing a reach task. The 27 conditions are color coded from green through black to red, based on the level of plan-period activity. D - 4 example PSTHs from the RNN sM1 circuit chosen to highlight the similarity of dynamics between neurons in M1 and sM1. E - Projection of monkey j3 data onto first jPC plane, from 1. F - Projection of sM1 data onto first jPC plane. This jPC plane explained 23% of the variance of sM1 activity. G - Cartoon provided in 1 to provide an intuition for how M1 might organize the cross-condition mean with respect to the rotations in the jPC plane. The cross-condition mean takes system trajectories from all ICs together to the oscillatory region and back again. H - A phase space diagram of sM1 activity during preparatory and movement phases across all 27 conditions. The visualized subspace is spanned by the two jPC vectors and an additional vector that captures the variance of the first principal component of the cross-condition mean (axis in red). Colored circles show the ICs provided by the preparatory input to the RNN. During movement, the sM1 dynamics move towards the jPC plane, yielding the rotational dynamics that ultimately drive the simulated spinal cord circuits to produce their respective EMG.
Translational and Computational Motor Control (TCMC) 2012
an exciting day of movement research!

Friday Oct 12, 9:00am - 8:00 pm
Hilton New Orleans Riverside
Room: Grand Salon B
Morning Session (Translational): 9am-1pm
Afternoon Session (Computational): 2pm-8pm

2012 Program:

9:00 am – 10:35 am

Plenary Lecture: From Synapse to Hemisphere – Imaging Recovery after Stroke – Nick Ward

Short- and long-term plasticity associated with peripheral nerve injury
Galit Pelled

The Importance of Mouse Medial Premotor Cortex, Early Re-Training, and Fluoxetine In The Recovery From a Focal Stroke Induced Motor Deficit
Steven Zeiler, Ellen Gibson, Robert Hoesch, Ming Li, Paul Worley, Richard O’Brien, John Krakauer

Multisensory Integration of Vision and Intracortical Microstimulation for Sensory Substitution and Augmentation
Maria Dadarlat, Joseph O’Doherty, Philip Sabes

10:35 am – 11:25 am: Poster Session/Break

11:25 am – 1:00 pm

Plenary Lecture: The Potential of Robots for Neurological Assessment – Steve Scott

Merging and Fractionation of Muscle Synergies as Physiological Markers of Motor Cortical Damage
Vincent C. K. Cheung, Paolo Bonato, Emilio Bizzi
Evidence for central and sensory drive in human stepping
Virginia W., Chu T., George Hornby, Brian Schmit

Spatiotemporal analysis of multi-stroke drawing movements in Parkinson’s disease reveals an impaired speed-accuracy tradeoff.
Leonie Asboth, Jordan Brayanov, Maurice Smith, Daniel Press

1:00 pm – 2:00 pm: Lunch Break

2:00 pm – 3:45 pm

Plenary Lecture: Neurogenetic Modulation of Reinforcement Learning Parameters – Michael Frank

Variability-Driven Predictive Control of Grip Forces
Alkis Hadjiosif, Maurice Smith

Multiple learning processes operate continuously throughout learning
Jordan Taylor, John Krakauer, Richard Ivry

A Recurrent Neural Network that Produces EMG from Rhythmic Dynamics
David Sussillo, Mark Churchland, Matt Kaufman, Krishna Shenoy

3:45 pm – 4:15 pm: Poster Session/Break

4:15 pm – 5:45 pm

Adaptation of Feedback Control and Voluntary Reaching Behaviour
Tyler Cluff, Stephen Scott

Motor adaptation and the proprioceptive estimates of limb state
Max Berniker, Konrad Kording

Optimal control predicts human and animal behavior in tasks with competing goals
Vassilios Christopoulos, Paul Schrater, Richard Andersen

Internal models engaged by brain-computer interface control
Matthew Golub, Byron Yu, Steven Chase

5:45 pm – 6:15 pm Poster Session/Break

6:15 pm – 8:00 pm

Uncovered hidden ability of nondominant arm for bimanual action
Atsushi Yokoi, Masaya Hirashima, Daichi Nozaki

Neural synergies constrain the acquisition of abstract Brain-Machine Interface skill
Andrew Jackson, John Barrett, Thomas Hall, Jennifer Tulip, Kianoush Nazarpour

Is there a reaching speed that minimizes metabolic cost?
Helen Huang, Alaa Ahmed

Plenary Lecture: A New Model of Motor Coding – Dan Margoliash
Clinical & Translational Posters (Morning Session):

Characterizing post-injury transcallosal plasticity with patch clamp recording
Ya Yang, Yan Jouroukhin, Galit Pelled

Visualizing real-time changes in expression of immediate early genes associated with plasticity
Yan Jouroukhin, Assaf Gilad, Galit Pelled

Long term plasticity in a pediatric rat model of traumatic brain injury
Nan Li, David Glover, Manda Saraswati, Courtney Robertson, Galit Pelled

Short-afferent inhibition during different movement phases of finger flexion
Mike Asmussen, Mark Jacobs, Kevin Lee, Chris Zapallow, Aimee Nelson

Dynamic gating of error signals during cerebellum-dependent learning
Rhea Kimpo, Jacob Rinaldi, Christina Kim, Karl Deisseroth, Jennifer Raymond

Stroke damage to the posterior parietal cortex provides causal evidence for its involvement in visual-to-motor transformations of reach targets
Aarlenne Khan, Laure Pisella, Gunnar Blohm

Changes in the location of Cortico-muscular coherence following stroke
Holly E Rossiter, Christiane Eaves, Marie-Helene Boudrias, Chang-hyun Park, Gareth Barnes, Vladimir Litvak, Simon Farmer, Nick S Ward

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Intuitive bimanual tasks for robotic assessment
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Task interference in constraint-induced movement therapy revealed by graph structure learning
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Cafeteria diet-induced metabolic syndrome: incorporating human disease co-morbidity in preclinical stroke models
Mariana Gomez-Smith, Carine Nguemeni, Matthew Jeffers, Dale Corbett
3D Robotic training in chronic stroke improves motor control but not motor function
Vincent S. Huang, Sophia L. Ryan, Leslie Kane, Sylvia Huang, Jessica R. Berard, Tomoko Kitago, Pietro Mazzoni, John W. Krakauer

Long-term Decoding Stability without Retraining for Intracortical Brain Computer Interfaces
William Bishop, Cindy Chestek, Vikash Gilja, Paul Nuyujukian, Stephen Ryu, Krishna Shenoy, Byron Yu

Computational Posters (Afternoon Session):

The identification of a rapidly-decaying, high-precision proprioceptive sensory memory and its effects on motor adaptation
Andrew Brennan, Howard Wu, Maurice A Smith

Sensitivity of movement vigor to changes in rate of reward
Thomas Reppert, Pavan Vaswani, Reza Shadmehr

Motor generalization: the effects of training breadth
Max Berniker, Hamid Mizraei Buini, Konrad Kording

Using parallel force clamps to quantify human adaptation to assistive and resistive perturbations
Ellisha Marongelli, Alexandra Foshage, Paul Wanda, Kurt Thoroughman

The temporal dynamics of parietal gain fields preclude their being used by the motor system to determine target position in space.
Michael Goldberg, Benjamin Xu, Carine Karachi

How Does Error Amplification Improve Task Performance?
Christopher Hasson, Masaki Abe, Dagmar Sternad

What takes time in the reaction time? Deciding task goals or specifying motor commands?
Adrian Haith, David Huberdeau, John Krakauer

Evidence for a forward update in state estimation following mechanical perturbations
Frédéric Crevecoeur, Stephen Scott

Goal-Equivalent Trial-to-Trial Control of a Generalized, Redundant Reaching Task
Jonathan Dingwell, Rachel Smallwood, Joseph Cusumano

and the special COSMO Summer School poster:

Effect of Baseline Variability in Motor Learning: Meta-analysis over multiple data sets
Moria Fisher*, Farnaz Abdollahi*, J. Ryan Morehead, Keturah Bixby

MORE NEWS SOON
Advances in Computational Motor Control 2011

Organized by Emo Todorov and Konrad Kording.

Session 1: 1:00 - 2:45

Invited talk: Motor learning
Reza Shadmehr

Structure of motor variability predicts differences in motor learning rates
Yohsuke Miyamoto, Howard Wu, Bence Ölveczky and Maurice A Smith

Modeling transfer of opposite visuomotor adaptation of the digits of the same hand
Willemijn Schot, Eli Brenner and Jeroen Smeets

Feedback-dependent generalization of visuomotor adaptation
Jordan Taylor and Richard Ivry

Break: 2:45 – 3:00

Session 2: 3:00 – 4:30

On the origins of motor noise
Kris Chaisanguanthum, Helen Shen and Philip Sabes

Motor coordination is habitual rather than optimal
Aymar de Rugy, Gerald Loeb and Timothy Carroll

Movement mechanics and muscle activity do not fully explain reductions in energetic cost
Helen Huang, Rodger Kram and Alaa Ahmed

Energy conservation principle in natural human movements
Dongsung Huh and Terrence Sejnowski

Coffee break: 4:30 – 5:00
Session 3:  5:00 – 6:45

**Invited talk:** The cerebellum
Timothy Ebner

**Purkinje cells compute sensory prediction errors**
Laurentiu Popa, Angela Hewitt and Timothy Ebner

**Inactivation of PRR induces hypometric reaches similar to optic ataxia**
EunJung Hwang, Markus Hauschild, Melanie Wilke and Richard Andersen

**An optimal control model of the compensatory eye movement system**
Ginzburg, M., Sibindi T., Frens. M. and and Donchin, O.

Posters and coffee:   6:45 – 8:00

**Generalization patterns reveal that visuomotor adaptation is composed of two distinct components**
Jordan Brayanov, Biljana Petreska and Maurice Smith

**Movement Adaptation under Conditions of Risk and Instability**
Michael Trent and Alaa Ahmed

**The representations of reach endpoints in posterior parietal cortex depend on which hand does the reaching**
Steve Chang and Lawrence Snyder

**Internal models and their many coordinate frames**
Max Berniker and Konrad Kording

**Minimum acceleration with constraints of center of mass: A unified model for arm movements and object manipulation**
Raz Leib and Amir Karniel

**Decoding arm kinematics from ECoG Signals in humans during a reach task**
Chandan Reddy, Oliver Flouty, Hiroto Kawasaki, Hiroyuki Oya, Lee Miller and Matthew Howard III

**Testing whether humans have an accurate model of their own motor uncertainty in a speeded reaching task**
Hang Zhang, Nathaniel Daw and Laurence Maloney

**Selection of arm movements during evidence accumulation**
Jason Friedman and Matthew Finkbeiner

**Evidence for model-free learning during force field adaptation**
Adrian Haith, Sarah Pekny, Reza Shadmehr and John Krakauer

**Seeking safe strategies for transporting complex objects**
Christopher Hasson, Tian Shen and Dagmar Sternad
Proceedings of the Annual Symposium

Advances in Computational Motor Control

Emanuel Todorov, Reza Shadmehr and Konrad Kording (editors)

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Zachary Danziger and Ferdinando Mussa-Ivaldi

The incremental adaptive effect of movement observation differs from that of action
Paul Wanda and Kurt Thoroughman

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The Relationship Between the Temporal Structure of Motor Output Variability and Motor
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Howard Wu, Gary Sing, Logan Clark, Luis Nicolas Gonzalez Castro, Maurice Smith

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Infinite-horizon optimal control framework for goal-directed movements
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Movement duration is selected to maximize the expected rate of reward
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A computational model of adaptation to novel stable and unstable dynamics
D. Franklin, R. Osu, E. Burdet, M. Kawato and T. Milner

Interpreting motor adaptation results within the framework of optimal feedback control
E. Todorov
Minimization of jerk, not torque change or end point error, mimics human movement in
dynamically perturbing environments
K. Thoroughman and W. Wang

A model of dimensionality reduction in goal-oriented motions
E. Torres

Patterns in stroke patients’ submovements support adaptive forward/inverse learning model
B. Rohrer, H. Krebs, B. Volpe, W. Frontera, J. Stein and N. Hogan

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